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Final Report on the MURI Program on the 'Realization and Integration of Large Lattice Mismatched Materials for Device Innovation: A Comprehensive Approach to the Underlying Science and Practical Application'

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14. ABSTRACT

Critical DoD need for advanced, high performance, multi-functional devices and circuits is addressed in this work. The underlying technology need is materials integration: the monolithic or polylithic assembly of functional materials and devices and the generation of device structures for which no lattice-matched substrate exists. A comprehensive program in the growth, integration, and device fabrication of large lattice mismatched materials is being carried out. Both new approaches to the engineered nucleation and motion of dislocations, as well as Critical

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ABSTRACT

Critical DoD need for advanced, high performance, multi-functional devices and circuits is addressed in this work. The underlying technology need is materials integration: the monolithic or polylithic assembly of functional materials and devices and the generation of device structures for which no lattice-matched substrate exists. A comprehensive program in the growth, integration, and device fabrication of large lattice mismatched materials is being carried out. Both new approaches to the engineered nucleation and motion of dislocations, as well as Critical DoD need for advanced, high performance, multi-functional devices and circuits is addressed in this work. The underlying technology need is materials integration: the monolithic or polylithic assembly of functional materials and devices and the generation of device structures for which no lattice-matched substrate exists. A comprehensive program in the growth, integration, and device fabrication of large lattice mismatched materials is being carried out. Both new approaches to the engineered nucleation and motion of dislocations, as well as advances in full wafer and sparse integration techniques applicable to a broad cross-section of materials are undertaken.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. “Highly-Strained InAs quantum wells on InP substrates for mid-IR emission”, Sangho Kim, Jeremy Kirch, Luke Mawst, J. Crystal Growth, 312 (2010) 1388-90.
2. “Growth Behavior and Defect Reduction in Heteroepitaxial InAs and GaSb Using Block Copolymer Lithography”, Smita Jha, Monika K. Wiedmann, T. S. Kuan, Xueyan Song, S. E. Babcock, and T. F. Kuech, J. Crystal Growth, 315 (2011) 91-95.
3. Book Chapter, Metal Organic Vapor Phase Growth of Complex Semiconductor Alloys, Thomas F. Kuech, AIP Conference Proceedings, v 1270, 8-92, 2010.
4. “Block Copolymer Templating for Formation of Quantum Dots and Lattice-Mismatched Semiconductor Structures”, S. Jha, C.-C. Liu, J. H. Park, M. K. Wiedmann, T. S. Kuan, S. E. Babcock, L. J. Mawst, P. F. Nealey, and T. F. Kuech, Mater. Res. Soc. Symp. Proc. 1258(2010) 1258-Q13-05.
5. “A comparative precursor study of the growth behavior of InSb using metal-organic vapor phase epitaxy”, Smita Jha, Monika K. Wiedmann, and T. F. Kuech, J. Crystal Growth, 315 (2011) 87-90.
6. “Narrow Band Gap GaInNAsSb Material Grown by Metal Organic Vapor Phase Epitaxy (MOVPE) for Solar Cell Applications”, T. J. Garrod, J. Kirch, P. Dudley, S. Kim, L. J. Mawst, T. F. Kuech, 315 (2011) 68-73.
7. “Effects of Antimony (Sb) Incorporation on MOVPE Grown InAsyP1-y Metamorphic Buffer Layers on InP Substrates”, Jeremy Kirch, TaeWan Kim, Jonathen Konen, L. J. Mawst, T.F. Kuech, Tung-Sheng Kuan, J. Crystal Growth, 315 (2011) 96-101.
8. “Thermal Characteristics of III/V Thin Film Edge Emitting Lasers on Silicon”, Sabarni Palit, Jeremy Kirch, Luke Mawst, Thomas Kuech, and Nan Marie Jokerst, International Journal of Microwave and Optical Technology 5 (2010) 483-7.
9. “High quality InP layers transferred by cleavage plane assisted ion-cutting”, Wayne Chen,Wnnie V. Chen, Kangmu Lee, S.S. Lau, and T.F. Kuech, Electrochemical and Solid-State Letters, v 13, n 8, p H268-H270, 2010.
10. “Dislocation Reduction In CdTe Epilayers Grown On Silicon Substrates Using Buffered Nanostructures”, S. Shintri, Sunil Rao, Huafang Li, I. Bhat, S. Jha, C. Liu, T.F. Kuech, W. Palosz, S. Trivedi, F. Semendy, P. Wijewarnasuriya, and Yuanping Chen, Proceedings of the SPIE, v 7768, p 77680A, 2010.
11. “ Growth of size and density controlled GaAs/InxGa1-xAs/GaAs (x=0.10) nanowires on anodic alumina membrane-assisted etching of nanopatterned GaAs”, Aloysius A. Gunawan, S. Jha, T.F. Kuech, J. Vacuum Sci. Technol. B, v 28, n 6, 1111-1119, 2010.
12. “High electron mobility transistors on plastic flexible substrates”, Wayne Chen, T.L. Alford, T.F. Kuech, and S.S. Lau, Applied Physics Letters, 98 (2011) 203509-11.
13. “Ion-cut transfer of InP-based high electron mobility transistors”, Wayne Chen, T.L. Alford, T.F. Kuech, and S.S. Lau, Journal of the Electrochemical Society, 158 (2011) H727-H732.
14. “Quantum dot active regions based on diblock copolymer nanopatterning and selective MOCVD growth”, L.J. Mawst, J.H. Park, Y. Huang, J. Kirch, T. Kim, C.-C. Liu, P.F. Nealey, T.F. Kuech, Y. Sin, and B. Foran, IEEE Winter Topicals, WTM 2011, (2011) 33-34.
15. “Nanopatterned quantum dot active region lasers on InP substrates”, L.J. Mawst, J.H. Park, Y. Huang, J. Kirch, Y. Sinc, B. Foranc, C. -C. Liu, P.F. Nealey, T.F. Kuech, Proc SPIE 7953 (2011) 795304-15.
16. “Facet-embedded thin-film III-V edge-emitting lasers integrated with SU-8 waveguides on silicon”, S. Palit,J. Kirch, Mengyuan Huang, L.Mawst, N.M. Jokerst, Optics Letters, 35 (2010) 3474-6.

Number of Papers published in peer-reviewed journals: 16.00

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. “Metamorphic Solar Cells Employing Chemical Mechanical Polishing and MOVPE Regrowth”, Luke J. Mawst, Peter Dudley, Jeremy Kirch, TaeWan Kim1, Steven Ruder, Thomas F. Kuech, Rao Tatavarti, 37th IEEE Photovoltaic Specialist Conference, Seattle, Washington, June 19-24, 2011.
2. “Growth of Ultra High Density InGaN-Based Quantum Dots on Self-Assembled Diblock Copolymer Nanopatterns”, Guangyu Liu, Hongping Zhao, Jing Zhang, Joo Hyung Park, Luke J. Mawst, Nelson Tansu, IEEE/OSA Conference on Lasers and ElectroOptics (CLEO), San Jose CA, May 2010.
3. “Cooperative Effects in the Incorporation of Nitrogen into GaAsN Using Mixed Nitrogen Sources”, Thomas Kuech, Claudio Canizares, and Luke Mawst, International Conference on Metalorganic Vapor Phase Epitaxy (ICMOVPE), Reno NV, May 23-28, 2010.
4. “Quinternary GaInAsSbP on GaAs Substrates Grown by Metal Organic Vapor Phase Epitaxy (MOVPE)”, Toby Garrod, Peter Dudley, Jeremy Kirch, Sangho Kim, Luke Mawst, and Thomas Kuech, TMS Electronic Materials Conference (EMC), Notre Dame University, June 2010.
5. “Metalorganic Vapor Phase Epitaxial Growth of (211)CdTe on Nanopatterned (211)Ge/Si Substrates Using Full Wafer Block Copolymer Lithography”, Shashidhar Shintri, Sunil Rao, Huafang Li, Smita Jha, C. Liu, Thomas Kuech, Witold Palosz, Sudhir Trivedi, Fred Semendy, Priyalal Wijewarnasuriya, Yuanping Chen, Ishwara Bhat, TMS Electronic Materials Conference (EMC), Notre Dame University, June 2010.
6. “InxGa1-xAs Metamorphic Buffer Layers for Lattice Mismatched Multi-Junction Solar Cells”, P. Dudley, J. Kirch, T. Garrod, S. Kim, L. J. Mawst, K. Radavich, S. Ruder, T. F. Kuech, S. Palit, N. M. Jokerst, TMS Electronic Materials Conference (EMC), Notre Dame University, June 2010.
7. “Nanoscale Block Co-polymer Processing for Selective Area Chemical Vapor Deposition,” Thomas F. Kuech, Smita Jha, Chi-Chun Li, Paul Nealey, Luke Mawst, Susan Babcock, Tung-Sheng Kuan, American Institute of Chemical Engineering Annual Conference, Salt Lake City, UT, Nov. 11, 2010.
8. “Quantum dot active regions based on diblock copolymer nanopatterning and selective MOCVD growth”, L.J. Mawst, J.H. Park, Y. Huang, J. Kirch, T. Kim, C.-C. Liu, P.F. Nealey, T.F. Kuech, Y. Sin, and B. Foran, IEEE Winter Topicals, WTM 2011, Keystone, CO, January 10-12, 2011.
9. “Characteristics of step-graded InxGa1-xAs and InGaPySb1-y Metamorphic Buffer Layers on GaAs substrates”, Jeremy Kirch, Peter Dudley, Tae Wan Kim, Katie Radavich, Steven Ruder, Luke Mawst, Thomas F Kuech, Stephen LaLumondiere, Yongkun Sin, William Lotshaw, Steven Moss, InP and Related Materials Conference, Berlin, Germany, May 23-26, 2011.
10. “Ion-cut Transfer of InP-Based High Electron Mobility Transistors Using Adhesive Bonding”, Wayne Chen, Christopher Doran, Thomas Kuech, S. S. Lau, TMS Electronic Materials Conference (EMC), University of California - Santa Barbara, Santa Barbara, California, June 22-24, 2011.
11. “Nanopatterned quantum dot active region lasers on InP substrates”, L. J. Mawst; J. H. Park; Y. Huang; J. Kirch; Y. Sin; B. Foran; C.-C. Liu; P. F. Nealey; T. F. Kuech, SPIE Photonics West, San Jose, CA, Jan 21-26, 2011.

Number of Presentations: 11.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Received		Paper
2007/09/08 1	6	D. P. Xu, M. D'Souza, J. C. Shin, L. J. Mawst, D. Botez. InGaAs/GaAsP/AlGaAs, deep-well, quantum-cascade-laser structures grown by metal organic chemical vapor deposition, ( )
2007/08/30 1	5	J. Y. T. Huang, D. P. Xu, J. H. Park, L. J. Mawst, T. F. Kuech, X. Song, S. E. Babcock, I. Vurgaftman and J. R. Meyer. Characteristics of strained GaAs1-ySby (0.16<y <0.69) quantum wells on InP substrates , ( )
2007/08/30 1	4	D. P. Xu, J. Y. T. Huang, J. Park, L. J. Mawst, T.F. Kuech X. Song, S.E. Babcock, . Annealing of dilute-nitride GaAsSbN/InP strained multiple quantum wells, ( )
2006/11/21 1	3	N. Liu, T.F. Kuech. Interfacial Chemistry of InP/GaAs Bonded Pairs, ( )
2006/09/15 1	2	P.F. Nealey, T.F. Kuech, L.J. Mawst, S.M. Park, A.A. Khandekar, J.H. Park. Selective MOCVD Growth of Single Crystal Dense GaAs Quantum Dot Array Using Cylinder-Forming Diblock Copolymers, ( )
2006/07/25 1	1	Peng Chen, S.S. Lau, N. David Theodore, Lin Shao , M. Nastasi. Effects of Hydrogen Implantation Conditions on the Trapping of Hydrogen in InP, Applied Physics Letters ( )

TOTAL: **6**

Number of Manuscripts:

Books

16. Book Chapter, Metal Organic Vapor Phase Growth of Complex Semiconductor Alloys, Thomas F. Kuech, AIP Conference Proceedings, v 1270, 8-92, 2010.

Patents Submitted

Patents Awarded

Awards

T.F. Kuech, UW-Foundation Chair Beckwith-Bascom Professorship, 2011-

T.F. Kuech, Humboldt Research Award, 2011

T.F. Kuech, Fellow of the IEEE, 2010

L.J. Mawst, Fellow of the IEEE, 2010

T.F. Kuech, Boelter University Lecturer, University of California, Los Angeles, 2010

T.F. Kuech, Visiting Fellow, Institute for Advanced Studies, Hong Kong University of Science and Technology, Hong Kong, 2011-

T.F. Kuech, Honorary Professor, Department of Physics, Nanjing University, Nanjing China, 2010.

Graduate Students

NAME	PERCENT_SUPPORTED
Steven Ruder	0.42
Claudio A Cañizares	0.25
Sabarni Palit	1.00
Wayne Chen	1.00
Kevin Schulte	0.09
Jeremy Kirch	0.12
FTE Equivalent:	**2.88**
Total Number:	**6**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Madhavie Edirisooriya	0.30
FTE Equivalent:	**0.30**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Thomas F Kuech	0.09	Yes
Susan E. Babcock	0.09	No
T.S. Kuan	0.09	No
Nan M. Jokerst	0.00	No
Luke J. Mawst	0.00	No
S. S. Lau	0.00	No
April S. Brown	0.00	No
FTE Equivalent:	**0.27**	
Total Number:	**7**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	
Cedric Mayers	0.20	No
Katherine A Radavich	0.20	No
Steward Swift	0.20	No
FTE Equivalent:	**0.60**	
Total Number:	**3**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	2.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	2.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	1.00

Names of Personnel receiving masters degrees

NAME	
Claudio A Cañizares	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Smita Jha	
Subarni Palit	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED	
Tong-Ho Kim	0.07	No
FTE Equivalent:	**0.07**	
Total Number:	**1**	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Final Summary for the MURI on '*Realization and Integration of Large Lattice Mismatched Materials for Device Innovation: A Comprehensive Approach to the Underlying Science and Practical Application'*

This MURI program looked to innovative means to integrate large lattice mismatched materials through changes in the epitaxial growth process and the recent advances in materials bonding. These complimentary approaches were used to create new materials and materials structures which could not be previously achieved. The program also benefitted from an additional finding increment to pursue the use of nanopatterning as a template for defect reduction.

Supplementary Funding and extended impact: There was an additional funding increment in year three directed at the acceleration of the research addressing issues related to the nanopatterning and use in forming devices, specifically GaSb growth on thin buffer layers, ternary $GaAs_xSb_{1-x}$ thin buffer layers, and ternary $In_xGa_{1-x}Sb$ thin buffer layers. We developed and published on this topics providing the information to the technical transfer partners. The Army Research (Patrick Folkes and Michael Gerhold) and Naval Research Laboratories were specifically interested in these subjects. In some cases, this work has also lead to separately funded spin-off projects of specific interest to ARL personnel but not within the initial scope of the proposed work. We have directly interacted with the scientists at these laboratories. An additional thrust was the use of nanoscale patterning to the area of infrared detectors. Several face-to-face discussions with DARPA (N. Dhar) were held providing the results and direction for the application of these techniques to substrates used in the formation of HgCdTe detectors. We initiated and published on the use of these nanopatterned for the formation of CdTe-based substrates.

The following is a summary of the key accomplishments for program.

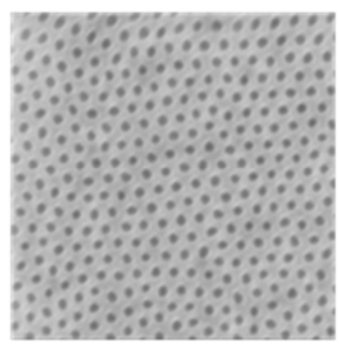


Figure 1: The BCL process allows for the formation of 20 nm PMMA cylinder in a matrix of polystyrene. This cylinder pattern can be transferred to an underlying dielectric mask and used in growth.

A. Defect reduction and alternative materials: Nanopatterning as a means to affect defect reduction

This MURI program developed the use of block co-polymer patterning and selective area growth as a means to dramatically reduce the threading dislocation density during large lattice mismatch growth. The integration of strain-relaxed, lattice-mismatched materials through direct epitaxial growth is impeded by the generation of a high density of mismatch dislocations needed to accommodate the difference in lattice parameters of these materials. Selective area epitaxy has often been employed for defect reduction in lattice-mismatched systems. In the cases of InAs and GaSb growth on GaAs substrates, which has a ~7% lattice mismatch, lateral epitaxial overgrowth (LEO) on micron-scale patterns has resulted in modest reductions in the threading dislocation densities. These LEO-based epitaxial growth techniques, however, have not led to a large decrease in the threading dislocation density. The micron-scale patterning used in past studies was not effective in altering the primary mechanisms of defect introduction and propagation. Typically, the reduction in the defect density was on the order of the ratio of the non-masked to total surface area, suggesting that the defect generation process is the same in the mask openings as it is on the mask-free substrates. Nanoscale patterning followed by selective growth was developed and demonstrated here to constrain the size of the growing material to within nanometer-sized mask openings. The relaxation of the epitaxial materials with such nanoscopic dimensions has the potential to provide alternative relaxation pathways which are not accessible on planar or larger area growth. Nanoscale selective area growth allows for the introduction of mismatch dislocations and hence strain relaxation, at the very initial stages of growth while the growth is still confined to the nanoscopic pattern. These islands can approach complete strain relaxation prior to coalescence of the film. Strain relaxation in small islands can reduce the threading dislocation density in the subsequent thicker overgrowth. We have initially demonstrated this approach to defect reduction for the growth of GaSb on nanopatterned GaAs substrates. Use of nano-patterned GaAs templates as the substrate led to substantial defect reduction and significant improvements in the material properties of GaSb films grown on these templates. The nanopatterned substrates were formed using block co-polymer lithography (BCL). This full-wafer spin-on technology allows for the formation over the entire wafer of a nanopattern with typical feature sizes of 20nm circular regions centered 40 nm apart as seen in Figure 1. In that initial study, a dramatic decrease in the threading dislocation density was shown. This work was extended to the use of BCL nanoscale patterns for defect reduction in the growth of InAs and InSb on GaAs templates. Both the growth behavior and the surface morphology of InAs on the nanopatterned GaAs exhibits a significantly different growth behavior than GaSb which is related to the nature of the surface transport processes associated with In surface diffusion on the SiO_2 BCL template surface. InAs and GaSb both exhibit a reduction in threading dislocations as a consequence of their growth on the nanopatterned GaAs.

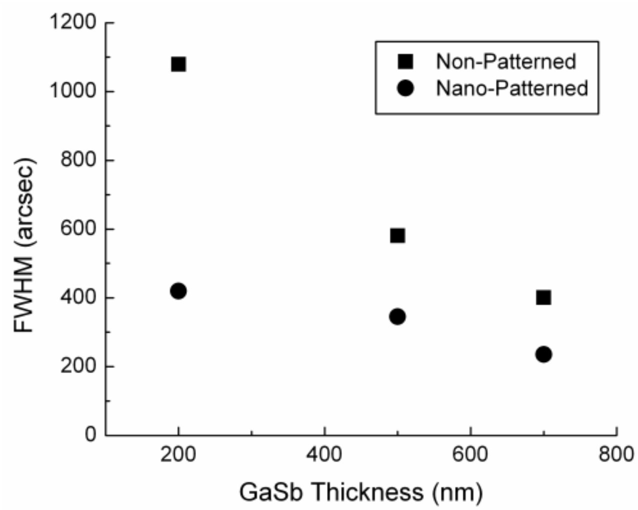
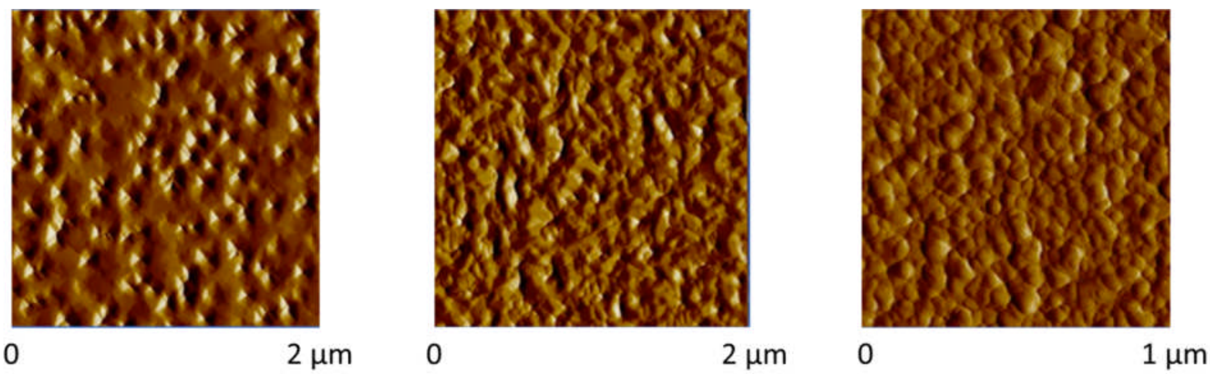


Figure 2: The drop in x-ray rocking curve line width is indicative of the reduced defect density in the GaSb films grown on a GaAs nanopatterned substrate.

The strain relaxation processes which led to the reduced defect density observed for the BCL-patterned films has been attributed to the nature of strain relaxation in nanoscopic islands in comparison to planar films. Strain relaxation during island growth has been studied both experimentally and theoretically. If strain relaxation can occur before film coalescence, particularly at a size scale commensurate with dislocation climb distance and the typical extent of the mismatch dislocation half loops in the heterophase interface, the island can become strain-relaxed with few dislocation threading segments. This implies that there is a pattern size scale associated with a given lattice mismatch for which the island can become fully relaxed prior to film coalescence. If the pattern size is much smaller than this characteristic distance associated with dislocation nucleation and motion, the nano-patterned template will not lead to a subsequent substantial reduction in the defect density. Only when the pattern dimension or the island size is larger than the critical wavelength for strain-induced surface rippling, which is the prelude to island formation, will defect introduction be expected.

This work was extended to the growth large lattice mismatched materials by molecular beam epitaxy (MBE). Unlike the previous MBE approaches in selective area growth for defect reduction, the small distances associated with the BCL pattern proved effective. The short diffusion lengths present on the MBE growth surfaces requires a small pattern in order to achieve a planar surface. As shown in Figure 3, the comparison between surfaces achieved for InAs on GaAs, with and without the BCL-based pattern. Previously in this project, and consistent with the literature, we observe a strong dependency of nucleation and surface diffusion on substrate material and on intermediate buffer structure. Using nm-scale BCL-based substrates, enhanced control of nucleation and strain relaxation was achieved. Figure 3 shows the surface roughness of InAs grown on Si was improved by nearly a factor of 4 when a nanopatterned substrate was used as a growth substrate.



T_{growth}=350°C on non-patterned GaAs
RMS Roughness: 20 nm

T_{growth}=350°C on non-patterned Si
RMS Roughness: 20 nm

T_{growth}=250°C on BCL-patterned Si
RMS Roughness: 20 nm

Figure 3: InAs films grown on non-patterned GaAs and Si and BCL-patterned Si. All films are 50 nm thick.

This approach is a general approach to the problem of large lattice mismatched growth which needs to be further developed beyond the MURI program. The approach is based on the fundamental dynamics of dislocation which is common to all compound semiconductors. It is an inexpensive, full-wafer, spin-on technology which could provide the most general method of materials heteroepitaxial integration.

B. Patterned QD lasers: First demonstration of a patterned QD active region laser on InP substrate.

While the preceding accomplishment describe the use of BCL-based patterning to reduce defect densities in the case of the large lattice mismatch growth, this patterning can also be used in lattice matched growth. In this case improvements in the performance of quantum dot lasers can be realize through the elimination of the wetting layer present in strain layer quantum dot growth. The diblock copolymer nanopatterning process, consisting of a series of pattern-transfers from a dense array of nano-sized holes in a diblock copolymer thin film to a dielectric template mask, allowed for the patterned access to the InP substrate for selective growth of the QDs. SiN_x (10 nm) / InP(100) substrates were employed using the diblock copolymer process and selective MOCVD growth. High density (~$6x10^{10}$ cm^{-2}) quantum dots (Figure 4a) were selectively grown (at 610^oC), consisting of InGaAsP Q1.15μm (2nm)/ $In_{0.53}Ga_{0.47}As$ (2nm)/InGaAsP Q1.15μm (2nm) forming the active region of a laser structure (Figure 4b). The TEM image, shown in Figure 3, indicate that the QDs are formed without a wetting layer. This is a significant accomplishment, since such structures will provide full three dimensional carrier confinement, as compared with SK self-assembled QDs.

Laser operation (J_{th}~$1.1KA/cm^2$ at 20K) is observed, Figure 5, from devices with 50 μm–wide stripes and 3.6 mm-long cavities up to temperatures of 170K. Based on the shorter emission wavelength (~1.3 μm) observed here, compared with that of the LT PL spectral peak (~1.4 μm), it appears that lasing may occur on a higher energy (excited state) QD transition. Further improvements in QD growth and pre-etching, are expected to lead to ground state emission with lower current densities. However, this is an important accomplishment since these data represent the first report of nano-patterned QD active region lasers on an InP substrate.

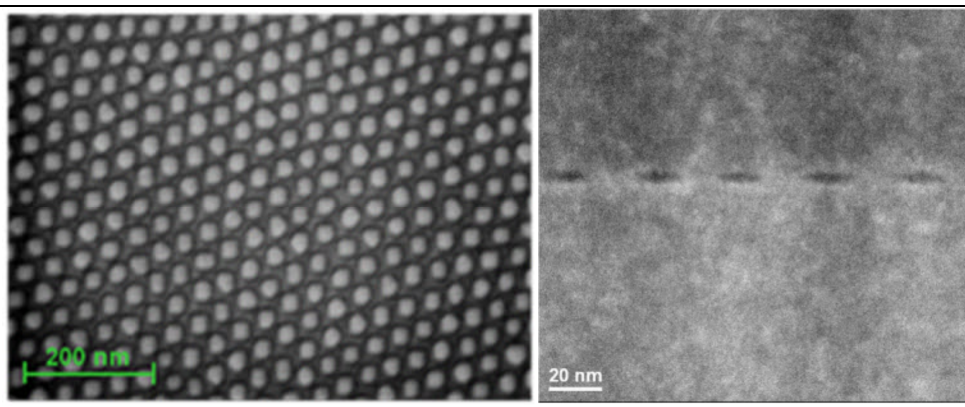


Figure 4. a) Top view SEM image of InGaAsP(Q1.15)/$In_{0.53}Ga_{0.47}As$/InGaAsP(Q1.15) QDs after selective MOCVD growth, b) TEM cross-sectional image of the buried QD active region, demonstrating QDs with no wetting layer present.

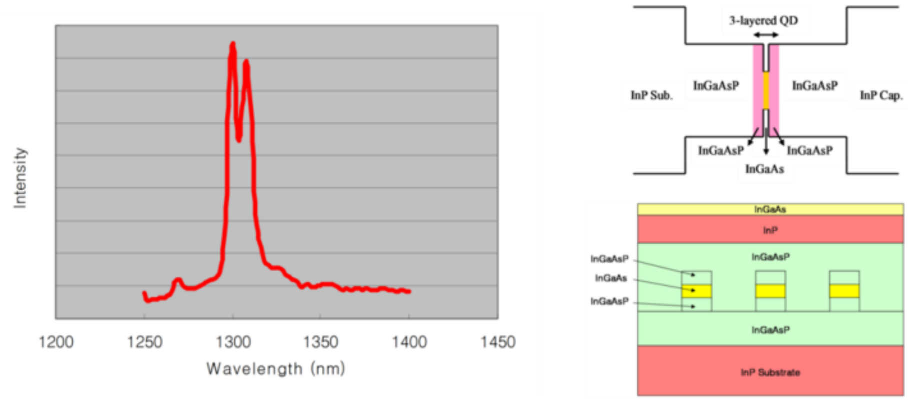


Figure 4.a) First demonstration of laser oscillation (shown here at 20K) from a nanopatterned QD active region device on an InP substrate, b) schematic diagram of the nano-patterned active laser structure.

This accomplishment allows for a whole new class of quantum dot lasers and structures previous unachievable. We have demonstrated that quantum dots structures can be grown without a wetting layer, we have demonstrated and increased processing range of growth temperatures, since the growth process now relies on selective area growth and not self-assembly, and finally we have demonstrated the formation of *lattice-matched* quantum dot structures. Since self-assembly is not required of the growing material, lattice matched structures can be grown which should open the process design window and increase the reliability of these structures.

C. Metamorphic Buffer Layers (MBL) on InP substrate: Demonstrated a novel step-graded InPSb MBL on InP

In parallel to the nanopatterning effort, we have developed new buffer layer structures based on multinary materials. The effects of antimony incorporation and a convex compositional step-gradient on the surface morphology, defect generation, and defect propagation properties of $InAs_yP_{1-y}$ Metamorphic Buffer Layers (MBLs) were investigated. The incorporation of Sb reduces the root-mean-square (RMS) of the surface roughness, and complete elimination of the arsenic from the MBL (i.e. InP_ySb_{1-y}) leads to a reduction of RMS values of the surface roughness from 16 nm ($InAs_yP_{1-y}$) to 3.4 nm (InP_ySb_{1-y}), without noticeably altering the defect density in the upper layers of the MBL. $InP_{1-y}Sb_y$ layers grown on an InP_ySb_{1-y} MBL have reduced hillock formation and exhibit energy band gaps within 8% of that expected from theory.

We have successfully grown GaInNAsSb material with band gaps in the range 1.13 to 1.29eV, nominally lattice matched to the GaAs substrate. These materials are close to the 'magic' band gap for multi-junction high-efficiency solar cells and are enabled by the formation of new metamorphic buffer layers combined with potential lift-off and transfer technologies. Secondary ion mass spectroscopy (SIMS) has been utilized on selected GaInNAs and GaInNAsSb samples in order to determine the actual compositions of constituent elements. Nominally lattice matched, bulk films have compositions of $GaIn_{(0.07)}N_{(0.03)}As$ (1eV) and $GaIn_{(0.02)}N_{(0.012)}AsSb_{(0.01)}$ (1.29eV), respectively. Preliminary annealing studies show a similar blue shift in PL wavelength with the GaInNAsSb material as seen with GaInNAs, on the order of 0.035eV. We investigated Sb incorporation in MBLs on GaAs substrates for solar cell applications. Specifically, we have developed a novel MBL design employing a step-graded InGaPSb on a GaAs substrate. Initial results indicate that this type of MBL exhibits low surface roughness (~4.7nm) compared with the InGaAs MBLs (7.3nm).

These new buffer structures has reduced the thickness required for the formation of more conventional, buffer-layer, approaches to materials integration and allows for the generation and integration of materials with a reduced layer thickness and decreased defect density.

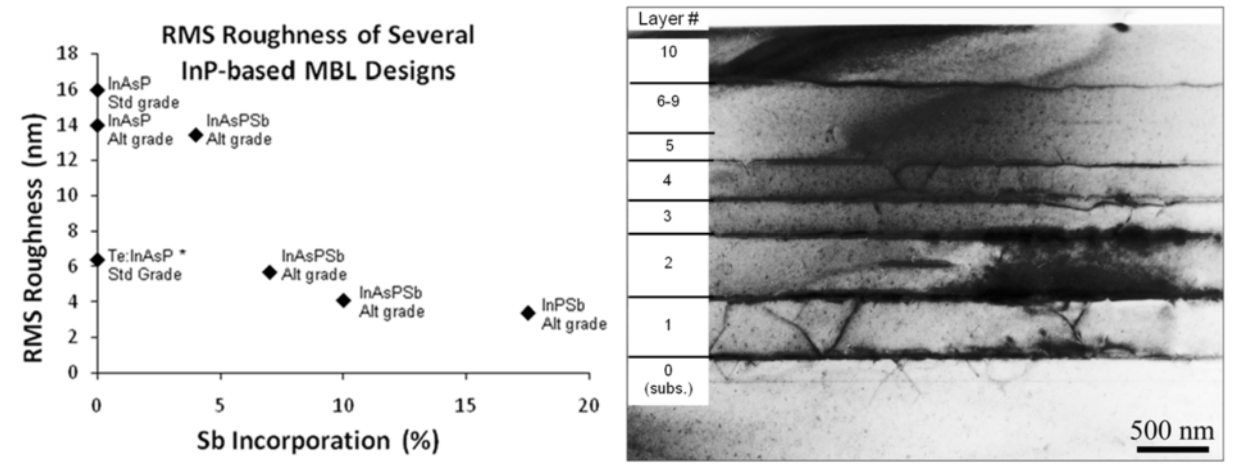


Figure 5a) Plot of the RMS values of the surface roughness for the base MBLs which were investigated in this study. *The Te-doped (~1x10^{19} cm^{-3}) InAsP MBL reference sample using the standard compositional gradient was provided by J. Cederberg at Sandia National Labs (unpublished), b) Cross-sectional TEM image of the InPSb MBL.

D. Direct transfer of Laser onto Silicon

The ability to pattern on both sides of a materials structure prior to integration onto another platform, such as Si, allows for the development of new functionality and performance. Additionally, strained layer can be incorporated into these structures by the materials design wherein the entire structure is strain-compensated. We have designed and implemented such a novel structure. A III-V thin film single quantum well edge emitting laser is patterned on both

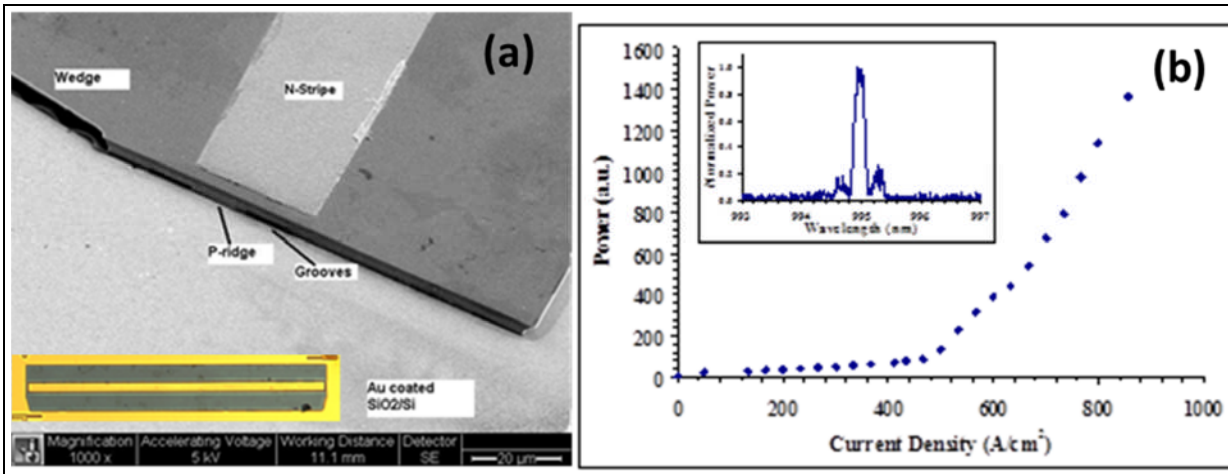


Figure 6: (a) SEM cross section of p-ridge/stripe laser with photomicrograph of laser bonded to metal contact on Si in inset (b) L-I characteristic for *p*-ridge/stripe laser with p-stripe of 10 µm, *p*-ridge of 15 µm, *n*-stripe of 30 µm, and laser cavity length of 1000 µm. Inset: Spectrum indicating lasing at a wavelength of 994.95 nm and laser line width of 0.187 nm.

sides of the epitaxial layer and bonded to Si. Injected threshold current densities of 420 A/cm^2 for gain guided lasers with bottom p-stripe and top n-stripe, and 244 A/cm^2 for index guided bottom p-ridge and top n-stripe lasers are measured with a lasing wavelength around 994 nm. These threshold current densities, among the lowest for thin film edge emitting lasers on Silicon reported to date, enable the implementation of integrated applications such as power-efficient portable chip-scale photonic sensing systems. This laser work holds, to the best of our knowledge from the published literature, the record for lowest threshold current density for a narrow line width thin film laser. It is the second lowest reported threshold current density for all thin film lasers (and all thin film lasers bonded to Si). This accomplishment relies on the additional current and optical confinement afforded by the two-side processing and the greatly improved thermal conductivity of the Si substrate. The removal of the GaAs (or InP) and the functional replacement by the Si should allow for greeter heat extraction, leading to improved stability as performance. This accomplishment and approach opens the range of device design and a means to integrate lasers, and hence optical communication, with the chip environment.

E. New methods for total device transfer and integration: Ion-cut Transfer of Devices

The transfer of finished device structures is a key technology for the development of integrated systems. Presently, while layers can be transferred, the formation of a finished, or nearly finished, device structure within it native technology with a subsequent transfer has been difficult. During the MURI, the development of ion-based (ion-cut) processes, which allow complete device structure to be transferred and integrated after device fabrication, have been developed. This process utilizes two bond-and-release steps referred to as 'double-flip' to allowing the finished device(s) to be removed from their native substrate and bonded onto a wide spectrum of substrate platforms, including sapphire, Si and plastic. Most recently, the double-flip

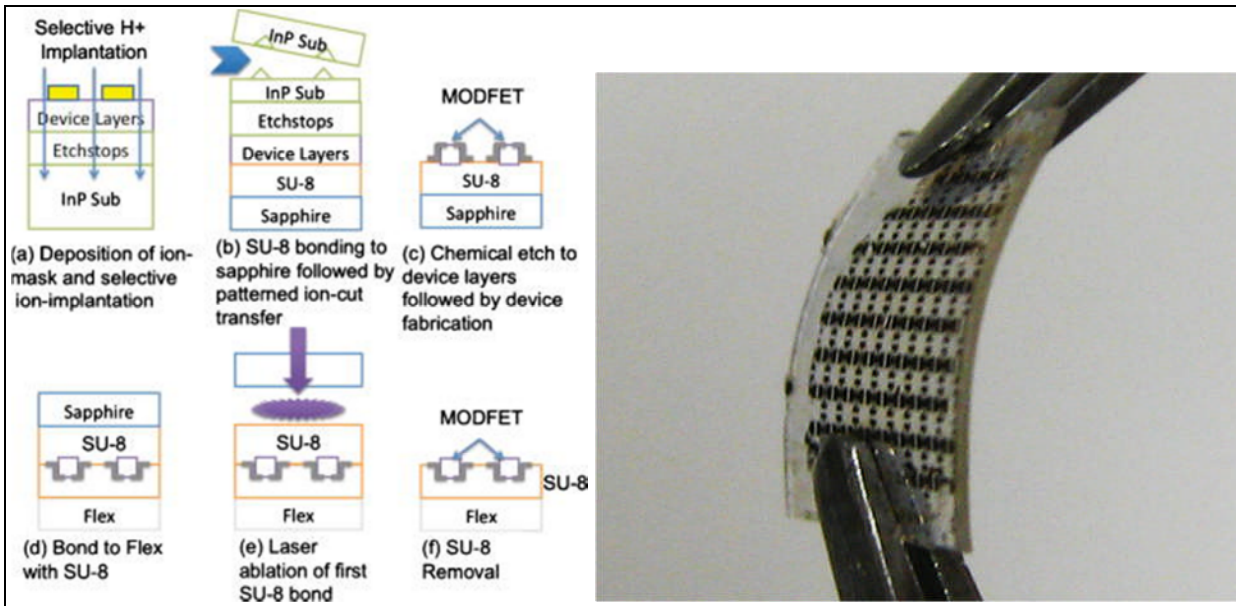


Figure 7: Process flow for device onto flexible substrate. This process flow can be used with other substrates and device materials

transfer of indium phosphide (InP) based transistors onto plastic flexible substrates was demonstrated. Modulation doped field effect transistor layers, epitaxially grown on InP bulk substrates, were transferred onto sapphire using a masked ion-cutting process. Following layer transfer, transistors were fabricated at low temperatures ($\leq$ 150 °C). The device structure was then bonded to flexible substrate, and laser ablation was used to separate the initial bond. The transferred transistors were characterized and exhibited high field-effect mobility ($\mu_{average}$~2800 $cm^2 V^{-1} s^{-1}$). Ion-cut layer transfer of (110) InP was also investigated as an alternative to (100) InP. The use of (110) InP allows for the cleavage plane to be parallel to the substrate surface facilitating transfer. InP donors were patterned-masked allowing for selective hydrogen implantation. The implanted wafers were bonded to acceptor substrates and transfer was initiated. The surface of the transferred regions was observed to be flatter than those obtained on (100) InP. Hall effect measurements showed the mobility in the masked regions to be unaffected by transfer. The process is extendable to the transfer of finished device structures into integrated systems.

This approach has allowed forth generation of new integrated structures wherein the devices are formed within their native technologies and then integrated into a larger platform. The performance advantage is achieved over the formation of post-transferred layers into devices since optimal temperatures processing and techniques can be used. The ion-cut, patterned approach permits a host of new substrates to be used.